

## Transforming Canada's Housing Stock: A Comprehensive Categorization of Sustainable Retrofit Strategies for Residential Building

Basil Ayyub Khan<sup>1</sup>, Ghobadi, Mehdi<sup>2</sup>, Kartik Patel<sup>1</sup>, Rajeev Ruparathna<sup>1,3\*</sup>

<sup>1</sup> Department of Civil and Environmental Engineering, University of Windsor, Windsor, ON, Canada

<sup>2</sup> National Research Council Canada, Ottawa, ON, Canada

<sup>3</sup> [rajeev.ruparathna@uwindsor.ca](mailto:rajeev.ruparathna@uwindsor.ca)

**ABSTRACT:** Single-family detached and attached homes constitute a significant portion of Canada's housing stock, many of which were constructed during the pre-sustainability era. Given their substantial energy demand, retrofitting these buildings is essential for meeting Canada's climate action goals. With a wide range of retrofit options available to reduce energy use, improve comfort, and enhance aesthetics, it is crucial to identify solutions that not only improve environmental performance but also generate positive economic and social impacts. Few resources currently classify residential building retrofits based on their primary focus. This study investigates retrofit strategies for Canada's single-family homes by evaluating their impact on building performance and categorizing innovative hybrid approaches that balance energy efficiency, cost-effectiveness, aesthetic appeal, and structural resilience. Our findings indicate that implementing hybrid retrofit strategies in Canada's residential sector requires an integrated approach addressing technical, financial, and regulatory challenges. Moreover, a structured classification of retrofit types, combined with robust stakeholder engagement beyond mere financial incentives, is essential to achieving significant improvements in energy efficiency, sustainability, and resilience. Ultimately, this research provides a framework for transforming existing residential buildings into energy-efficient, visually appealing, and regulation-compliant homes.

Keywords: Residential Buildings, Retrofits, Climate Action, Asset Management

### 1. INTRODUCTION

The global imperative to reduce carbon emissions has positioned energy-efficient retrofitting as a cornerstone of climate action strategies. Residential buildings account for a substantial proportion of global energy consumption, with the International Energy Agency (IEA) reporting that the built environment contributes nearly 28% of global CO<sub>2</sub> emissions (Energy Agency, 2021). Retrofitting existing housing stock is particularly vital, given the slow turnover rates in residential construction and the energy intensity of older buildings. Achieving the global net-zero target necessitates retrofitting approximately 20% of existing structures by 2030 (Energy Agency, 2021). The residential sector made up 13% of Canada's end-use energy demand, and 6% of its GHG emissions in 2021 (Canada Energy Regulator, 2023). According to 2019 Survey of Household Energy Use, In Canada, over 50% of residential buildings are more than 30 years old, and over 20% are older than 50 years (Government of Canada, 2020). These buildings were created prior to incorporating energy efficiency into buildings codes (Government of Canada, 2023). Retrofitting residential buildings is essential for achieving a low-carbon built environment, as older homes often consume excessive energy due to outdated insulation, heating systems, and inefficient materials, contributing significantly to greenhouse gas emissions (Canada Green Building Council, 2024). The above retrofits can be more cost-effective in the long term compared to demolishing and rebuilding. The initial

investment in upgrades is often offset by lower operational costs, including reduced utility bills, maintenance expenses, and even potential property value appreciation (Friedman *et al.*, 2014). In addition to energy efficiency, retrofitting supports the longevity and resilience of the building. Moreover, many old buildings are not designed to withstand the increasing frequency of extreme weather events caused by climate change. Incorporating climate-resilient materials and designs during retrofitting can safeguard these structures against future weather-related challenges, further enhancing their value and lifespan (Government of Canada, 2024). A report by Pembina institute revealed that Canada needs to retrofit 600,000 existing homes to reach Net Zero Targets (Agar, 2024).

Fossil fuels are used extensively in residential buildings for heating and cooling, and energy inefficiency is made worse by antiquated technologies and poor thermal performance. During extreme weather events, high energy demand also makes the grid more dependent on non-renewable sources (Energy Agency, 2021). Retrofitting can improve grid stability by integrating renewable energy sources, lowering carbon footprints, and mitigating urban heat islands. However, differences in building age, materials, and energy performance make it difficult to choose cost-effective retrofit strategies. Financial limitations further impede decision-making, and homeowners frequently lack knowledge of their options (Tsenkova, 2021, Cetiner and Edis, 2014). Building retrofits have been mostly studied to cope with climate change and the need for energy demand reduction. However, to achieve the emission reduction target, retrofit strategies should be optimized to include trade-offs between the environmental, social, and economic impacts of building retrofits (Zhang *et al.*, 2021; Toufeili *et al.*, 2022). Retrofitting decisions should ideally be based on comprehensive building performance evaluations, but many existing tools fail to provide an integrated approach that considers energy efficiency, cost-effectiveness, and environmental impact (Golkar, 2021). Furthermore, policy gaps and inconsistencies in incentive programs often lead to confusion among homeowners, making it challenging to implement large-scale retrofitting initiatives (Canada Mortgage and Housing Corporation, 2021). The absence of standardized assessment frameworks also contributes to the challenge.

Retrofitting strategies are commonly classified by the depth of intervention, the specific building components they target (such as external insulation, glazing, or heating systems), and the desired outcomes in terms of energy savings and environmental impact reduction (Peng *et al.*, 2021). Categorization is essential for ensuring an effective and systematic approach to retrofitting, allowing stakeholders to prioritize interventions based on energy efficiency, cost-effectiveness, and long-term sustainability (Energy Agency, 2021). Retrofitting interventions generally fall into three primary categories: minor retrofits, major retrofits, and deep retrofits (Golkar, 2021). Minor retrofits, such as weather-stripping, caulking, and LED lighting, are relatively low-cost, quick-to-implement solutions that primarily reduce energy losses without requiring significant structural modifications (Tsenkova, 2021). Major retrofits involve extensive improvements to building components, including replacing outdated windows and doors with energy-efficient alternatives, upgrading HVAC systems with smart control technologies, and enhancing roof insulation to minimize heat loss, ultimately improving overall energy performance and cost-effectiveness (Ruggeri *et al.*, 2020; Streicher *et al.*, 2020). Deep retrofits, on the other hand, are comprehensive modifications that seek to achieve near net-zero energy performance by integrating renewable energy sources such as solar photovoltaic (PV) panels and geothermal heating, as well as implementing whole-building envelope insulation and air-sealing strategies (Finch and Hanam, 2013). Another way to categorize retrofits is based on the specific building components they target, such as insulation, HVAC systems, lighting, water heating, and ventilation (Canada Mortgage and Housing Corporation, 2021). Categorization is crucial because it enables policymakers to design targeted incentives and regulatory frameworks (Energy Agency, 2021), helps homeowners make informed decisions by identifying the most suitable retrofit measures for their needs and budgets (Natural Resources Canada, 2020), and facilitates better resource allocation by directing funds and subsidies toward interventions with the highest impact on energy savings and carbon reduction (Tsenkova, 2021). Without proper categorization, retrofitting initiatives risk being implemented in an ad hoc manner, reducing their effectiveness and scalability (Golkar, 2021). A structured approach enhances tracking and reporting of energy efficiency improvements, enabling governments and industry professionals to measure progress toward national and global climate goals (Canada Mortgage and Housing Corporation, 2021).

Despite the introduction of initiatives such as Canada’s Greener Homes Grant, current retrofit policies often adopt a fragmented approach. Most programs prioritize energy savings while neglecting broader sustainability objectives, including aesthetic improvements and social equity (Tsenkova, 2021). This singular focus not only limits their appeal to homeowners but also reduces their potential to achieve transformative impacts (Tsenkova, 2021). Moreover, the lack of standardized methodologies for evaluating retrofit outcomes complicates efforts to scale these initiatives effectively (Energy Agency, 2021).

A clear gap exists in the literature for holistic integrative assessments of retrofit strategies that concurrently measure energy performance with aesthetics, cost, and structural stability. This exploratory work tackles this gap by the assessment of retrofit strategies for single-family detached homes in Canada through multi-dimensional lenses. It emphasizes hybrid innovations finding a balance among energy efficiency, cost-effectiveness, aesthetic appeal, and structural resilience, which are key factors in promoting wider acceptance. By attempting a systematic classification of retrofitting interventions with regard to their extent of work, targeted building components, and sustainability objectives, this study gives a major foundation and some guidance for input into policies, future research direction, and aiding homeowners toward making more sustainable decisions with renovations.

## **2. LITERATURE REVIEW**

Retrofitting practices in Canada span a wide range of interventions—from minor upgrades like weather-stripping to comprehensive deep retrofits involving envelope overhauls and renewable energy integrations. Although these measures have yielded significant energy savings, their implementation often lacks a unified strategy aligned with broader sustainability goals (Finch and Hanam, 2013). Moreover, disparities in access to financial and technical resources between urban and rural areas further exacerbate inequities in retrofit adoption.

Global variations in retrofit efforts underscore the need for context-sensitive strategies. In developing regions, limited access to capital and a shortage of skilled labor hinder retrofitting efforts, while in developed nations, challenges such as high labor costs and fragmented supply chains impede progress (Energy Agency, 2021). For instance, the European Union’s “Renovation Wave” initiative highlights the critical role of public-private partnerships and policy harmonization in overcoming these obstacles (European Commission, 2020). Meanwhile, localized community-led initiatives in Canada have demonstrated considerable promise. Collaborations between municipal governments and non-profit organizations in cities such as Edmonton and Toronto have prioritized retrofitting underserved neighborhoods, thereby addressing systemic inequities while advancing sustainability goals (Golkar, 2021).

Recent empirical investigations have shed light on the practical application of hybrid retrofits in urban environments. Case studies conducted in Toronto and Vancouver provide a contextual foundation for understanding how these strategies are implemented (Finch and Hanam, 2013; Natural Resources Canada, 2020). These cities were selected owing to their proactive energy efficiency policies and diverse housing typologies, which make them ideal for evaluating retrofit interventions (Energy Agency, 2021; Tsenkova, 2021). Researchers have utilized a range of metrics—including energy savings, cost-effectiveness, and occupant satisfaction—to derive actionable insights. The findings reveal that hybrid retrofits hold significant transformative potential by achieving notable energy reductions while simultaneously enhancing the aesthetic and functional qualities of residential buildings (Energy Agency, 2021; Finch and Hanam, 2013). For instance, passive design retrofits in Vancouver have demonstrated up to a 50% reduction in heating loads (Golkar, 2021), and Toronto’s adoption of smart grid technologies illustrates the efficacy of digital tools in optimizing retrofit outcomes (Tsenkova, 2021).

Table 1 presents the diverse objectives of retrofitting strategies, and their classification based on scope. Minor retrofits serve as accessible entry points, major retrofits address structural inefficiencies, and deep retrofits offer transformative energy savings. Hybrid retrofits integrate these approaches, offering flexibility and scalability to address Canada’s diverse housing needs (Finch and Hanam, 2013; Natural Resources Canada, 2020). Hybrid retrofits address key limitations of traditional approaches by combining minor, major, and deep retrofit strategies (Finch and Hanam, 2013; Natural Resources Canada, 2020). For example, integrating renewable energy systems with structural and aesthetic improvements can simultaneously

reduce energy consumption, enhance property value, and improve occupant satisfaction (Golkar, 2021; Tsenkova, 2021). This approach aligns with Canada’s dual objectives of reducing emissions and improving housing affordability, especially in urban settings (Energy Agency, 2021; Natural Resources Canada, 2020). Additionally, hybrid retrofit strategies enhance adaptability by enabling homeowners to select measures that align with both their budget constraints and long-term sustainability ambitions, effectively balancing upfront investment with future energy performance gains (Wang *et al.*, 2015).

Table 1: Objectives of different retrofit types

Retrofit Type	Objective	Examples	Reference
Minor Retrofits	Reduce air leaks, enhance insulation	Weather-stripping, caulking, attic insulation	(Natural Resources Canada , 2020)
Major Retrofits	Improve structural systems, upgrade HVAC	Window replacements, HVAC upgrades	(Golkar, 2021)
Deep Retrofits	Achieving nearly net-zero energy performance	Solar panels, heat recovery ventilators	(Tsenkova, 2021)
Hybrid Retrofits	Balance energy, aesthetics, and resilience	Combined thermal, structural, and aesthetic upgrades	(Finch and Hanam, 2013)

Retrofitting single-family residential buildings involves a comprehensive approach that addresses multiple objectives to improve overall performance and occupant well-being. Enhancing energy performance is a primary goal, achieved through upgrading insulation, installing high-efficiency heating, ventilation, and air conditioning systems, and integrating renewable energy technologies, all of which reduce energy consumption and lower utility bills (Natural Resources Canada , 2020). Building resilience is another critical objective, ensuring that structures are better equipped to withstand extreme weather events, seismic activity, and other potential hazards, thereby safeguarding both property and lives (Government of Canada 2024). Indoor air quality is targeted through improved ventilation, the use of low-emission materials, and effective moisture management, which collectively reduce indoor pollutants and promote healthier living conditions. Additionally, retrofits often aim to boost thermal comfort and acoustical performance, creating more pleasant indoor environments. Aesthetic improvements, such as modernizing facades and updating finishes, can enhance a home’s visual appeal and potentially increase property value (Natural Resources Canada 2024). Cost-effectiveness and sustainability underpin many retrofit initiatives, with strategies designed to offer a favorable return on investment while reducing the overall environmental footprint. These multi-dimensional objectives reflect an integrated approach that not only addresses immediate energy concerns but also promotes long-term sustainability, occupant safety, and overall quality of life.

Table 2 presents a detailed mapping of retrofit measures categorized into minor, major, deep, and hybrid types, along with their corresponding sources. Each measure is linked to a specific peer-reviewed article, government report, or industry publication, ensuring transparency in source distribution. This breakdown supports the systematic literature review approach discussed in the Methodology section.

Table 2. Comprehensive Categorization of Retrofit Measures with Source Type

Retrofit Category	Retrofit Measure	Source	Source Type
Minor Retrofits	Weatherstripping	Natural Resources Canada (2020)	Government Report
	Caulking	Tsenkova (2021)	Peer-Reviewed Article

Major Retrofits	LED Lighting	Natural Resources Canada (2020)	Government Report
	Attic Insulation	Golkar (2021)	Industry Publication
	HVAC Upgrades	Golkar (2021)	Industry Publication
	Smart Thermostat	Energy Agency (2021)	Industry Publication
	External Wall Insulation	Finch and Hanam (2013)	Peer-Reviewed Article
	Thermal Cladding	Natural Resources Canada (2020)	Government Report
	Double-Glazed Windows	Tsenkova (2021)	Peer-Reviewed Article
	Tankless Water Heater	Golkar (2021)	Industry Publication
Deep Retrofits	Solar Panels	Tsenkova (2021)	Peer-Reviewed Article
	Green Roofs	Energy Agency (2021)	Industry Publication
	Geothermal Systems	Golkar (2021)	Industry Publication
	Advanced Air Barriers	Natural Resources Canada (2020)	Government Report
	Triple-Glazed Windows	Finch and Hanam (2013)	Peer-Reviewed Article
	Battery Storage Integration	Finch and Hanam (2013)	Peer-Reviewed Article
	Combined Heat and Power (CHP)	Energy Agency (2021)	Industry Publication
	Roof-Mounted Wind Turbines	Tsenkova (2021)	Peer-Reviewed Article
Hybrid Retrofits	Rainwater Harvesting	Golkar (2021)	Industry Publication
	Vacuum-Insulated Panels	Natural Resources Canada (2020)	Government Report
	Daylighting Systems	Tsenkova (2021)	Peer-Reviewed Article

### 3. METHODOLOGY

This study employs a systematic literature review methodology, synthesizing data from peer-reviewed journals, government reports, and industry publications to categorize retrofit strategies by their components, objectives, and outcomes. Key steps include:

- **Data Collection:** Sources were drawn from peer-reviewed journals, government reports, and industry publications to ensure a comprehensive overview of current retrofit practices.
- **Classification Framework:** Retrofits were methodically categorized by their scope, targeted building components, and sustainability objectives. This framework facilitated a detailed assessment of each strategy's impact.
- **Content analysis:** Each retrofit strategy was evaluated using performance metrics—including energy efficiency, cost-effectiveness, aesthetic appeal, and structural resilience—to determine overall building performance improvements. Each retrofits were assessed across eight performance dimensions: Energy performance, Aesthetics, Structural integrity, Resilience, Air Quality, Comfort, Noise Reduction, and Water Conservation.
- **Recommendations:** Innovative hybrid approaches were identified through comparative analyses, highlighting their potential to drive widespread adoption and offering actionable insights for policymakers, researchers, and homeowners.

This structured approach ensures a thorough examination of retrofit strategies, balancing technical performance with practical implementation considerations.

#### 4. CLASSIFICATION OF BUILDING RETROFITS

Table 3 categorizes retrofit strategies for single-family detached homes into four distinct types: Minor, Major, Deep, and Hybrid retrofits, each targeting specific building components to enhance overall performance (Natural Resources Canada, 2020).

- Minor retrofits focus on cost-effective, low-disruption interventions, such as roof weatherproofing and reflective coatings, LED bulb replacements for lighting, window caulking, and door weatherstripping. These measures offer immediate improvements in energy efficiency and building durability with minimal investment (Golkar, 2021).
- Major retrofits involve more comprehensive upgrades that address significant energy losses. For instance, enhancements to HVAC systems—such as installing high-efficiency furnaces and smart thermostats—external wall insulation, thermal cladding, double-glazed windows, and tankless water heaters aim to optimize energy consumption and indoor comfort while providing long-term savings (Tsenkova, 2021).
- Deep retrofits represent transformative interventions, incorporating renewable energy solutions and advanced building technologies. This category includes solar panel installations, green roofs, geothermal heating systems, advanced air barriers, triple-glazed windows, and battery storage integration, all designed to drastically reduce energy usage and emissions (Energy Agency, 2021).
- Hybrid retrofits blend multiple strategies for synergistic effects, combining technologies like combined heat and power systems, roof-mounted wind turbines, rainwater harvesting, and vacuum-insulated panels (Golkar, 2021). This comprehensive approach enhances both sustainability and performance by integrating diverse retrofit components (Tsenkova, 2021).

Table 3: Comprehensive Categorization of Retrofit Strategies Based on Type and Building Component

Type of Retrofit	Building Component	Retrofit	Reference
<b>Minor Retrofit</b>	Roof	Weatherproofing	(Natural Resources Canada, 2020)
	Roof	Reflective Coating	(Golkar, 2021)
	Lighting	LED Bulb Replacement	(Natural Resources Canada, 2020)
	Windows	Caulking	Tsenkova (2021)
	Doors	Weatherstripping	(Natural Resources Canada, 2020)
<b>Major Retrofit</b>	HVAC System	High-Efficiency Furnace	(Golkar, 2021)
	HVAC System	Smart Thermostat Installation	(Energy Agency, 2021)
	Walls	External Insulation	(Finch and Hanam, 2013)
	Walls	Thermal Cladding	(Natural Resources Canada, 2020)
	Windows	Double-Glazed Windows	(Tsenkova, 2021)
<b>Deep Retrofit</b>	Plumbing	Tankless Water Heater	(Golkar, 2021)
	Roof	Solar Panel Installation	(Tsenkova, 2021)
	Roof	Green Roof Implementation	(Energy Agency, 2021)
	HVAC System	Geothermal Heating System	(Golkar, 2021)
	Walls	Advanced Air Barriers	(Natural Resources Canada, 2020)
<b>Hybrid Retrofit</b>	Windows	Triple-Glazed Windows	Tsenkova (2021)
	Electrical System	Battery Storage Integration	(Finch and Hanam, 2013)
	HVAC System	Combined Heat and Power (CHP)	(Energy Agency, 2021)

Roof	Roof-Mounted Wind Turbines	(Tsenkova, 2021)
Plumbing	Rainwater Harvesting System	(Golkar, 2021)
Walls	Vacuum-Insulated Panels	(Natural Resources Canada, 2020)

Table 4 provides a systematic evaluation of retrofit measures for single-family residential buildings by mapping each intervention against eight key performance objectives: energy performance, aesthetics, structural integrity, resilience, air quality, comfort, noise reduction, and water conservation. Organized by retrofit sub-category, it presents a range of interventions—from basic measures like weather stripping, insulation upgrades, and LED lighting to advanced solutions such as triple-glazed windows and integrated HVAC systems.

Retrofit strategies are classified according to their scale and impact. Minor retrofits offer cost-effective, immediate gains; for example, weather stripping reduces air leaks, thereby enhancing energy performance, indoor comfort, and even contributing to improved structural integrity and resilience, while insulation upgrades boost thermal efficiency and aid in noise reduction and water conservation (Natural Resources Canada, 2020). Major retrofits involve substantial upgrades to critical systems, such as HVAC enhancements that incorporate high-efficiency furnaces and smart thermostats, significantly improving energy performance, air quality, and occupant comfort (Golkar, 2021). Deep retrofits target transformative changes, with solar panels serving as a prime example by generating renewable energy and reducing reliance on fossil fuels (Tsenkova, 2021). Hybrid retrofits combine elements from various categories to balance energy efficiency, resilience, comfort, and aesthetics—integrated HVAC systems, for instance, optimize indoor climate control while lowering energy costs (Energy Agency, 2021). Overall, Table 3 illustrates how each retrofit measure uniquely contributes to multiple performance dimensions, supporting informed decisions that enhance building sustainability and occupant well-being.

Table 4: Detailed Classification of Retrofits by Objectives and Impact on Building Performance

Retrofit Type	Sub category	Energy	Aesthetics	Structure	Resilience	Air Quality	Comfort	Noise Reduction	Water Conservation	Reference
<b>Minor Retrofits</b>	Weather stripping	✓				✓	✓			(Natural Resources Canada, 2020)
	Insulation Upgrade	✓					✓	✓		(Natural Resources Canada, 2020)
	LED Lighting	✓	✓				✓	✓		(Natural Resources Canada, 2020)
<b>Major Retrofits</b>	Door Sealing	✓				✓	✓			(Tsenkova, 2021)
	HVAC Upgrade	✓		✓		✓	✓			(Golkar, 2021)
	Roofing Enhancement	✓	✓	✓	✓		✓			(Golkar, 2021)
	Window Replacement	✓	✓	✓			✓	✓		(Golkar, 2021)

	Tankless Water Heater	✓		✓		✓	✓		✓	(Golkar, 2021)
<b>Deep Retrofits</b>	Solar Panels	✓		✓	✓					(Tsenkova, 2021)
	Geothermal Systems	✓		✓	✓		✓			(Tsenkova, 2021)
	Green Roofs	✓	✓	✓	✓	✓	✓	✓		(Golkar, 2021)
	Advanced Air Barriers	✓		✓	✓		✓			(Natural Resources Canada, 2020)
	Triple-Glazed Windows	✓	✓	✓	✓		✓	✓		(Finch and Hanam, 2013)
<b>Hybrid Retrofits</b>	Integrated HVAC System	✓	✓	✓	✓	✓	✓	✓		(Energy Agency, 2021)
	Combined Heat and Power	✓	✓	✓	✓	✓	✓			(Energy Agency, 2021)
	Vacuum-Insulated Panels	✓	✓	✓	✓		✓	✓		(Tsenkova, 2021)
	Roof-Mounted Turbines	✓	✓	✓	✓					(Golkar, 2021)
	Daylighting Systems	✓	✓				✓	✓		(Tsenkova, 2021)

This detailed classification provides stakeholders, including homeowners, engineers, and policymakers, with a roadmap for implementing retrofit strategies tailored to specific building components and sustainability goals (Energy Agency, 2021; Natural Resources Canada, 2020). Each building component—be it the roof, HVAC systems, windows, or plumbing—plays a crucial role in improving overall energy efficiency, comfort, and resilience. By addressing these components with targeted retrofit measures, Table 3 ensures that interventions align with environmental objectives and economic constraints while enhancing the functionality and livability of residential buildings (Energy Agency, 2021; Natural Resources Canada, 2020). The inclusion of benefits such as air quality improvement, noise reduction, and water conservation highlight the multifaceted advantages of retrofitting, ensuring that each measure contributes to a holistic transformation of Canada’s housing stock.

## 5. DISCUSSION AND CONCLUSIONS

Hybrid retrofit implementation in Canada’s residential sector presents a multifaceted challenge that demands the seamless integration of technical, financial, and regulatory components, alongside an in-depth understanding of building performance characteristics (Golkar, 2021). The diverse nature of Canada’s housing stock—spanning various construction techniques, ages, and architectural styles—necessitates tailored retrofit approaches. For instance, older single-family homes built before 1980 often require a combination of minor measures such as weatherstripping and insulation upgrades together with major interventions like HVAC system replacements to achieve significant energy savings (Tsenkova, 2021). In contrast, deep retrofits that incorporate renewable energy solutions—such as solar photovoltaic panels and geothermal systems—pose additional challenges regarding cost and technical feasibility, particularly when retrofitting buildings not originally designed for these advanced technologies (Finch and Hanam, 2013).

Jiang and Tovey (2010) identify four primary barriers to building energy efficiency: investment, informational, institutional/management, and technological. Investment barriers limit energy efficiency improvements to investors capable of shouldering high upfront costs, unless robust legislative and financial incentives are provided. Informational barriers stem from a lack of knowledge among building owners, managers, and occupants about potential energy savings and cost-effective energy management practices. Institutional and management challenges are evident in the inconsistent implementation of green building policies, with studies indicating that many organizations lack established energy-saving goals. Technological barriers, including the rebound effect, further complicate the realization of anticipated carbon and energy reduction targets.

Classifying retrofits into minor, major, deep, and hybrid categories is crucial for structured resource allocation and the development of targeted policies that address specific requirements (Ruggeri et al., 2020). This framework allows stakeholders to focus on interventions that maximize energy efficiency and minimize carbon emissions. Moreover, the integration of advanced tools like Building Information Modeling plays a pivotal role by enabling detailed energy performance simulations, creating standardized “retrofit families,” and automating energy analyses to customize retrofit designs to each building’s unique characteristics (Finch and Hanam, 2013; Natural Resources Canada, 2020).

Reviews of municipal retrofit programs in cities such as Vancouver and Toronto reveal that financial incentives alone are insufficient for widespread adoption. For example, while Vancouver’s deep retrofit initiatives have yielded notable energy reductions, their scalability remains limited by high upfront costs and low homeowner engagement (Golkar, 2021). These findings underscore the necessity for integrative approaches that couple technical innovations with robust stakeholder involvement. Moreover, the presented study only focused on single-family detached home and did not consider other types of residential buildings.

Future research should prioritize developing decision-support tools that leverage real-time data from Internet of Things (IoT) sensors to continuously monitor building performance post-retrofit, enabling precise, lifecycle adjustments (Energy Agency, 2021). Additionally, comprehensive field studies and longitudinal analyses are needed to validate the long-term benefits of hybrid retrofits in terms of energy savings, occupant satisfaction, and environmental impact (Tsenkova, 2021). Furthermore, other types of residential buildings should be considered in future research for more comprehensive analysis. Ultimately, by systematically categorizing retrofit strategies and addressing the spectrum of implementation challenges—from technical feasibility to policy alignment and data integration—this research aims to establish a comprehensive framework that enhances energy efficiency while bolstering the sustainability, affordability, and resilience of Canada’s housing stock, thus supporting national climate action goals and driving future innovations in retrofit methodologies (Prabatha et al., 2020).

## REFERENCES

- Agar, B. (2024), “Deep retrofits of buildings save more than just money”, available at: [https://www.pembina.org/blog/deep-retrofits-buildings-save-more-just-money#:~:text=Our new report%20Beyond Energy,reach 2050 net-zero targets.](https://www.pembina.org/blog/deep-retrofits-buildings-save-more-just-money#:~:text=Our%20new%20report%20Beyond%20Energy,reach%202050%20net-zero%20targets.) (accessed 20 September 2024).
- Canada Energy Regulator. (2023), *Canada’s Energy Future 2023*, Ottawa, ON.
- Canada Green Building Council. (2024), “Retrofits for the future”, available at: <https://www.cagbc.org/why-green-building/retrofits-for-the-future/> (accessed 20 September 2024).
- Canadian Mortgage and Housing Corporation (CMHC). (2021), *Building Housing Solutions Together CANADA MORTGAGE AND HOUSING CORPORATION*.
- Cetiner, I. and Edis, E. (2014), “An environmental and economic sustainability assessment method for the retrofitting of residential buildings”, *Energy and Buildings*, Vol. 74, pp. 132–140, doi: 10.1016/j.enbuild.2014.01.020.
- Energy Agency, I. (2021), *Energy Efficiency 2021*. International Energy Agency, Paris, France
- European Commission. (2020), “stakeholder\_consultation\_on\_the\_renovation\_wave\_initiative”.

- Finch, G. and Hanam, B. (2013), "Net zero building enclosure retrofits for houses: An analysis of retrofit strategies", *Thermal Performance of the Exterior Envelopes of Whole Buildings, Florida, USA*
- Friedman, C., Becker, N. and Erell, E. (2014), "Energy retrofit of residential building envelopes in Israel: A cost-benefit analysis", *Energy*, Vol. 77, pp. 183–193, doi: 10.1016/j.energy.2014.06.019.
- Golkar, P. (2021), *High-Level Building Energy Retrofit Strategies for BC Communities Maximizing GHG Emissions Reductions from Existing Building Sector in Different Case Study Communities-Maximizing the Effect of Local Government Effort*.
- Government of Canada. (2020), "2019 Survey of Household Energy Use (SHEU-2019) Data Tables", available at: <https://oee.nrcan.gc.ca/corporate/statistics/neud/dpa/menus/sheu/2019/tables.cfm> (accessed 25 September 2024).
- Government of Canada. (2023), "Canada's national energy code", available at: <https://natural-resources.canada.ca/energy-efficiency/buildings/new-buildings/canadas-national-energy-code/20675> (accessed 19 September 2024).
- Government of Canada. (2024), "Resiliency measures to protect your home", available at: <https://natural-resources.canada.ca/energy-efficiency/homes/canada-greener-homes-initiative/canada-greener-homes-grant/canada-greener-homes-grant/how-the-grant-process-works/resiliency-measures-protect-your-home/resiliency-measures> (accessed 25 September 2024).
- Jiang, P. and Tovey, K. (2010), "Overcoming barriers to implementation of carbon reduction strategies in large commercial buildings in China", *Building and Environment*, Elsevier Ltd, Vol. 45 No. 4, pp. 856–864, doi: 10.1016/j.buildenv.2009.09.004.
- Natural Resources Canada (NRCan). (2020), "Energy Use in Canada: Trends | Natural Resources Canada", available at: <https://oee.nrcan.gc.ca/publications/statistics/trends/2020/totalsectors.cfm> (accessed 16 February 2025).
- Natural Resources Canada (NRCan). (2024), "PEER – Prefabricated Exterior Energy Retrofit", available at: <https://natural-resources.canada.ca/energy-efficiency/peer-prefabricated-exterior-energy-retrofit> (accessed 16 February 2025).
- Peng, Z., Zhao, S., Shen, L., Ma, Y., Zhang, Q. and Deng, W. (2021), "Retrofit or rebuild? The future of old residential buildings in urban areas of China based on the analysis of environmental benefits", *International Journal of Low-Carbon Technologies*, Oxford University Press, Vol. 16 No. 4, pp. 1422–1434, doi: 10.1093/ijlct/ctab070.
- Prabatha, T., Hewage, K., Karunathilake, H. and Sadiq, R. (2020), "To retrofit or not? Making energy retrofit decisions through life cycle thinking for Canadian residences", *Energy and Buildings*, Elsevier Ltd, Vol. 226, doi: 10.1016/j.enbuild.2020.110393.
- Ruggeri, A.G., Gabrielli, L. and Scarpa, M. (2020), "Energy retrofit in european building portfolios: A review of five key aspects", *Sustainability (Switzerland)*, MDPI, 1 September, doi: 10.3390/SU12187465.
- Streicher, K.N., Mennel, S., Chambers, J., Parra, D. and Patel, M.K. (2020), "Cost-effectiveness of large-scale deep energy retrofit packages for residential buildings under different economic assessment approaches", *Energy and Buildings*, Elsevier, Vol. 215, p. 109870
- Toufeili, R., Ruparathna, R. and Tam, E. (2022), "A life cycle thinking centered methodology for energy retrofit evaluation", *Canadian Journal of Civil Engineering*, Vol. 49 No. 7, pp. 1239–1253
- Tsenkova, S. (2021), *Energy Efficient Affordable Housing: Policy Design and Implementation in Canadian Cities*, Springer International Publishing, doi: 10.1007/978-3-030-69563-7.
- UNFCCC. (2022), "Exploring Approaches for Canada's Transition to Net-Zero Emissions", pp. 1–67.
- Wang, Q., Laurenti, R. and Holmberg, S. (2015), "A novel hybrid methodology to evaluate sustainable retrofitting in existing Swedish residential buildings", *Sustainable Cities and Society*, Elsevier Ltd, Vol. 16 No. C, pp. 24–38, doi: 10.1016/j.scs.2015.02.002.
- Zhang, H., Hewage, K., Prabatha, T. and Sadiq, R. (2021), "Life cycle thinking-based energy retrofits evaluation framework for Canadian residences: A Pareto optimization approach", *Building and Environment*, Elsevier Ltd, Vol. 204 No. April, p. 108115, doi: 10.1016/j.buildenv.2021.108115.